

A Novel Temperature Sensor Based on Temperature-dependent Attenuation at 850nm of Irradiated Ge/P Co-doped Fiber

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Abstract. An all fiber-optic temperature sensor based on the temperature dependence of radiation-induced attenuation (RIA) of Ge/P co-doped optical fiber at 850 nm was proposed. The principle of the sensor was interpreted by the temperature dependence of color center absorption. Characteristics of the temperature sensor, such as dynamic range, sensitivity, linearity, and repeatability, were tested and analyzed. The dynamic range of the sensor was -40°C to 60°C, and the temperature sensibility was 0.1146dB/°C. The nonlinearity error and the repeatability error were respectively $\pm 2.75\%$ and 1.06%.

Introduction

With the development of the fiber-optic technology, fiber-optic temperature sensors are extensively used in industrial production. Compared with conventional temperature sensing devices, the fiber-optic temperature sensors have unique advantages: such as immunity to electromagnetic interferences, high stability, durability against harsh environments, high sensitivity, and so on [1,2]. Many kinds of temperature transducers have been developed based on different technology, like Fiber Bragg Grating [3], Fabry-Perot interferometers [4], and OTDR fiber-optic sensors [5,6]. According to our previous studies, the irradiated Ge/P co-doped fiber after thermal annealing has the potential to be used for temperature sensor.

In radiation environment, the attenuation of the optical fiber would increase greatly due to the formation of color centers, namely the trapping of radiolytic electrons and holes at defect sites in the fiber [7,8]. Many researches have demonstrated that the radiation-induced attenuation (RIA) in the optical fiber can be influenced by the temperature, and the RIA of most optical fibers exhibits a decreasing trend with the increasing temperature in most spectra range, with the exception of P core-doped fibers [9-14]. Some researchers explain this reverse behavior in P doped fibers by transforming the phosphorus oxygen hole center (POHC) into the P1 center [15,16]. For the Ge doped fiber and in the 300~900nm range, the RIA can be interpreted by absorption bands associated with the following radiation-induced point defects: Ge(1), Ge-NBOHC and GeX [17]. Many color centers, such as Ge(1), Ge-NBOHC, P1, and POHC, have been identified, and most of them exist in UV-visible absorption bands [10,17,18]. In [19], it has been mentioned that the color center absorption influencing the RIA at 1310 nm in the Ge/P co-doped fiber exhibits monotonic and remarkable temperature dependence. The temperature dependence of the color center absorption is proposed to explain the RIA behavior at the near infrared wavelengths according to the configurational coordinate model [20]. As the absorption bands of many radiation-induced defects are in the ultraviolet and visible ranges and can extend to the near infrared region, the RIA at shorter wavelength is supposed to be more sensitive to temperature. As previous studies indicate, the RIA of Ge/P co-doped optical fiber at 850 nm transmission wavelength is more sensitive to temperature than that at 1310 nm, and the temperature sensitivity and linearity in the fiber irradiated at a higher total dose are much better [21].

Therefore, the RIA at 850 nm of the Ge/P co-doped optical fiber irradiated at a total dose of 10,000 Gy was researched for temperature sensing fiber in this paper. And a novel all-fiber temperature sensor based on the temperature dependence of RIA was put forward.

The Theory of Temperature Sensor

According to what we have known, under thermal excitation, color centers can be annealed by releasing electrons or holes, which results in a degradation of the RIA. Theoretically, each kind of color centers has a steady temperature, under which color centers enable to be unchanged and form a stable light absorption in the optical fiber. Once above its steady temperature, color centers will be thermally driven annealed or transform into other kinds of color centers due to thermal excitation. When the number density of each kind of color centers in the optical fiber remains unchanged, the color center absorption probability and its absorption band shape rely on temperature, which results in the steady and regular change of the RIA with increasing temperature [10]. According to the steady temperature dependence stable color centers possessed, this paper investigated a novel fiber-optic temperature sensor by using the irradiated optical fiber after sufficient annealing.

Configurational coordinate model offers an analysis reference for the temperature dependence of color center absorption in the optical fiber. It explains how the electron potential energy curves changes with the varying average position of the electron [22], which is detailedly accounted for in [22] and [23]. It can be used to analyze the spectrum properties of color centers whose absorption bands are in Gaussian band shape [23,24].

For Ge/P co-doped optical fiber, the RIA is primarily related to color centers associated with Ge and P1 at UV and near infrared wavelengths [10,20,25]. In previous investigations, we find that the RIA spectra can be decomposed into several color center absorption spectra by using the configurational coordinate model, and in the 800~1600 nm range the RIA spectrum properties of Ge/P co-doped fibers are found to rely strongly on P1, Ge-NBOHC and GeX centers. Thus, the fitting function of RIA in Ge/P co-doped fibers can be expressed as formula (1) [20].

$$RIA(E, T) = a_{p1}(T) \exp\left[-\left(\frac{E - E_{p1}(T)}{\omega_{p1}(T)}\right)^2\right] + a_{GeX}(T) \exp\left[-\left(\frac{E - E_{GeX}(T)}{\omega_{GeX}(T)}\right)^2\right] + a_{Ge-NBOHC}(T) \exp\left[-\left(\frac{E - E_{Ge-NBOHC}(T)}{\omega_{Ge-NBOHC}(T)}\right)^2\right]. \quad (1)$$

In formula (1), T is temperature which should be lower than the annealing temperature, and E represents the photon energy. According to the configurational coordinate model, as temperature increases, the peak E_{p1} , E_{GeX} , and $E_{Ge-NBOHC}$ of the absorption spectrum will shift to lower energy region (longer wavelength), and the bandwidth ω_{p1} , ω_{GeX} , and $\omega_{Ge-NBOHC}$ will widen. In addition, the absorption intensity a_{p1} , a_{GeX} , and $a_{Ge-NBOHC}$ will decrease with the temperature increasing [24]. These changing parameter values with increasing temperature directly reflect the temperature dependent RIA.

By using formula (1), we simulated the RIA under T_1 and T_2 ($T_1 < T_2$) in the spectral range of 800~1600nm. It is obvious that the values of E and a under T_1 are smaller than that under T_2 , and the value of ω at T_1 is bigger than that under T_2 . Table 1 shows the parameter values of P1, Ge-NBOHC and GeX centers obtained at 20°C [18,20,25,26]. In order to simulate effectively, we suppose two groups of parameters respectively at T_1 and T_2 on the basis of the parameter values given in Table 1. The parameters used to simulate are given in Table 2.

Fig.1 gives the simulated result, which illustrates that the RIA is larger when the temperature is higher. Besides, the difference between the RIA under T_1 and the RIA under T_2 is decreasing with the wavelength increasing. Thus, the RIA at shorter transmission wavelength is more sensitive to temperature. The simulated result here accords with the experimental result in [21]. The simulation and previous experiment both indicate that the transmission wavelength of 850 nm is very appropriate for the temperature sensor.

Table 1 Main parameter values of P1, Ge-NBOHC and Ge(X) color centers

Color center name	E_n (eV)	ω_n (eV)
P1	0.765	0.224
Ge-NBOHC	1.97	0.3-0.6
Ge(X)	2.61	0.82

Table 2 Parameter values used to simulate

Color center name	$[E_{T1}, E_{T2}]$ (eV)	$[\omega_{T1}, \omega_{T2}]$ (eV)	$[a_{T1}, a_{T2}]$
P1	[0.766, 0.763]	[0.212, 0.228]	[1.242, 1.150]
Ge-NBOHC	[1.990, 1.957]	[0.507, 0.587]	[4.815, 4.690]
Ge(X)	[2.643, 2.590]	[0.800, 0.825]	[2.061, 2.047]

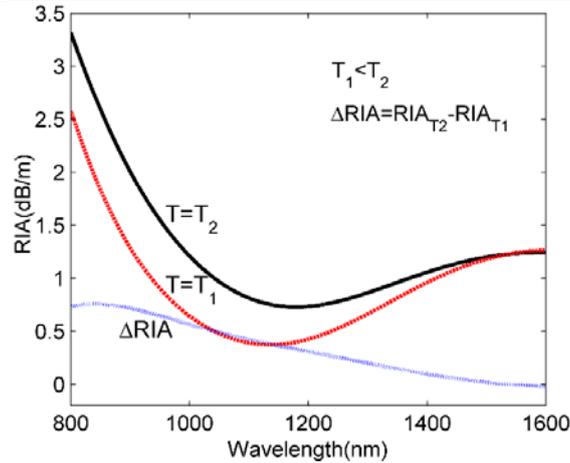


Fig. 1 Simulated RIA(E, T) at T_1 and T_2 ($T_1 < T_2$) in the spectral range of 800~1600nm.

Experiments and Experimental Results

In the experiments, the Ge/P co/doped optical fiber that was a commercial off-the-shelf (CTOS) optical fiber was chosen. The core of the optical fiber was Ge/ P co-doped, and the cladding and coating diameters of the chosen fiber were respectively 80 and 165 μ m.

The testing system of temperature sensor shown in Fig.2 was developed to measure the attenuation of the Ge/P co-doped fiber. And a temperature controlled chamber was used. The temperature is measured by digital temperature sensor (DS18B20) whose accuracy is $\pm 0.5^\circ\text{C}$ and resolution is 0.0625°C . A super luminescent diode (SLD) with the central wavelength of 850nm was used. The output optical signal of SLD was separated into two paths. One was used as reference to compensate for the variations of light intensity which was generated by photoelectric devices. The other was the temperature sensor head using the irradiated optical fiber. A multi-channel optical power meter was used to monitor the optical signals and the experimental data sent by the serial interface was processed in computer.

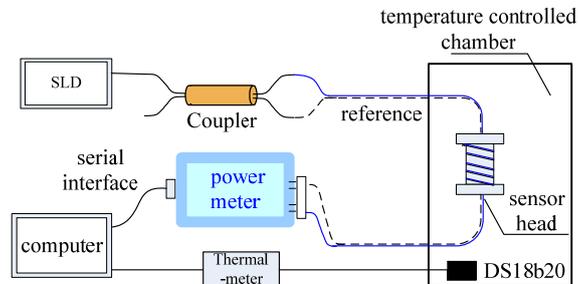


Fig. 2 A Schematic structure of a laboratory set-up for testing the fiber-optic temperature sensor.

The experiments can be divided into three stages. Firstly, the Ge/P co-doped fiber before irradiation was tested for two temperature cycles to observe the temperature behavior of the fiber loss. Fig.3 gives the normalized attenuation of Ge/P co-doped fiber before irradiation. The dash line is the real-time temperature in the temperature controlled chamber measured by DS18B20. It can be seen from the loss curve that the attenuation before irradiation is slightly fluctuant with temperature

varying. And the temperature dependence of the unirradiated optical fiber is not obvious and stable. In the two temperature cycles, the maximum variation is about 0.56dB/km.

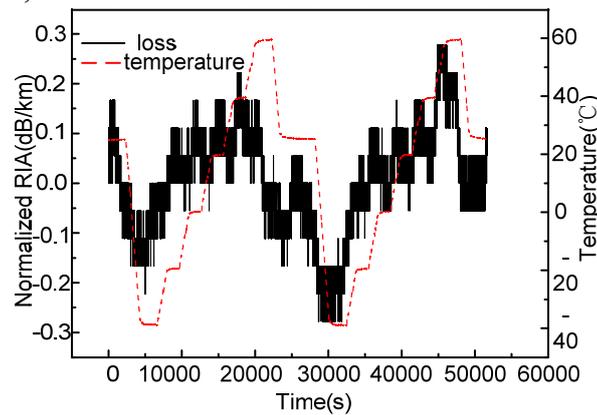


Fig. 3 Normalized attenuation by the attenuation measured at 20°C before irradiation

Secondly, the optical fiber was exposed to irradiation at a dose rate of about 25Gy/min up to a total dose of 10,000 Gy. The ⁶⁰Co gamma radiation source was used at room temperature. After irradiation, the fiber was initially annealed at room temperature for two weeks, and then at 70°C to accelerate the annealing process until the variation of attenuation could be neglected at 60°C. Thus the majority of unstable color center defects below 60°C were annealed and converted. However, the temperature inside the temperature controlled chamber is slightly fluctuant, which can result in variation of the fiber attenuation. Fig.4 gives the result of annealing which indicates that the maximum attenuation variation at 60°C of the irradiated fiber is 0.003dB during last 6 hours of the annealing process. Fig.4 illustrates that most of the unstable color centers formerly existing in the irradiated fiber have been annealed or transformed into other kinds of stable ones after sufficient annealing.

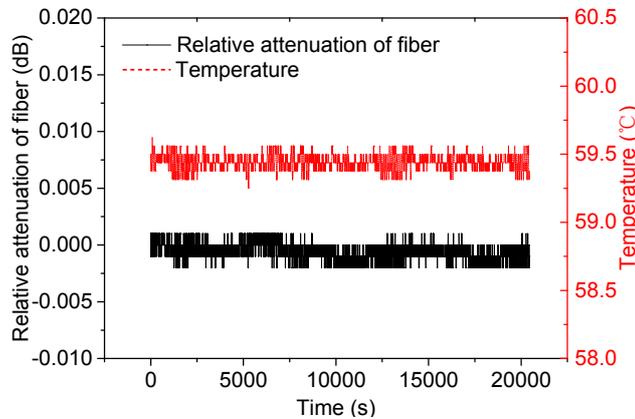


Fig. 4 The relative attenuation of fiber at 60°C

Fig. 5 gives the experiment data normalized by the value of attenuation at 20°C. As illustrated in Fig.4, before irradiation, the attenuation hardly changes with the varying temperature. After irradiation, the attenuation varies with temperature but the variation isn't stable. The increase of the attenuation in second temperature cycle indicates that there are unstable color centers existing in the fiber and some of them are annealed in the first cycle. After sufficient annealing, the radiation-induced attenuation shows monotonic temperature dependence in the range of -40~60°C. This experimental result further confirms that the Ge/P co-doped fiber at 850nm can be used to develop a novel fiber temperature sensor.

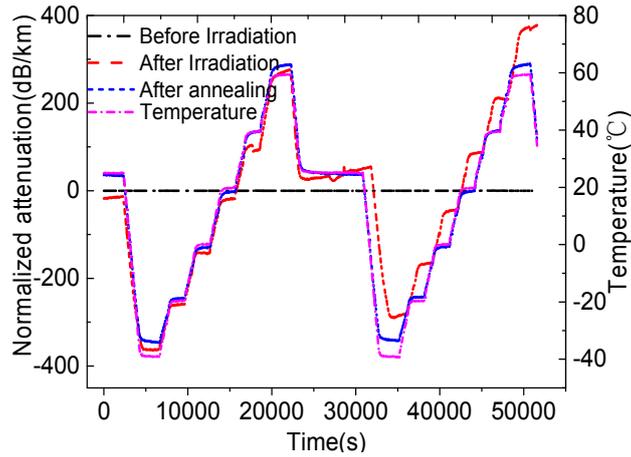


Fig. 5 The attenuation of Ge/P co-doped fiber at 850nm measured before irradiation, after irradiation but before thermal annealing and after sufficient thermal annealing, all data were normalized by the attenuation value measured at 20°C.

Finally, the irradiated and sufficiently annealed fiber was used as the temperature sensing head. The temperature behaviors of the optical fiber, including linearity, sensitivity, and repeatability, were researched. The measurement range of fiber-optic temperature sensor was controlled continuously from -40°C to 60°C with an interval of 10°C. Fig.6 gives the measuring result. Plotted in Fig.6 is the normalized radiation-induced attenuation at different temperatures ranging from -40°C to 60°C. It can be seen that the attenuation increases with the increasing temperature, and they are in a nearly linear relation. The solid line represents linear fitting line of the experimental data. The fitting line equation is as follows:

$$RIA_N(T) = 6.408T - 118.215 \quad (2)$$

In formula (2), $RIA_N(T)$ is the value of normalized attenuation.

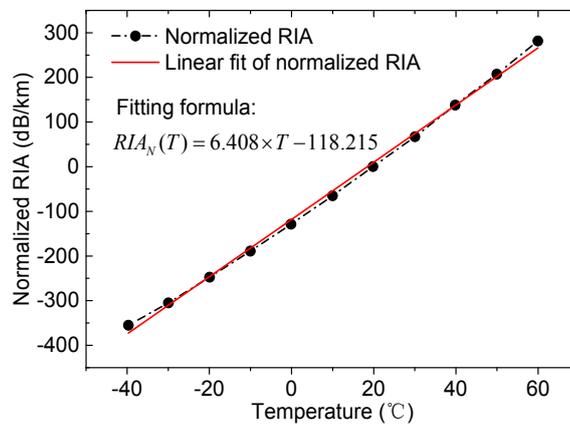


Fig. 6 The normalized RIA measured at different temperatures from -40°C to 60°C and its fitting curve.

The total attenuation variation is approximately 636.57dB/km in the entire temperature range. For the fiber sample with a length of 18m, the loss variation during the range of temperature is approximately 11.46dB. Thus the temperature sensibility of RIA in the testing fiber is about 0.1146dB/°C. Assuming that the minimum detection limit of the sensing system is 0.001dB, for the irradiated fiber of 18m, the minimum temperature variation that can be sensed is 0.008°C. The linearity of the temperature dependent RIA is obtained by the least square straight linear fitting of the experimental data. And the nonlinearity error is $\pm 2.75\%$ in this experiment.

In order to investigate the repeatability of temperature sensing system, the irradiated fiber is used to repeat five temperature tests. The repeatability, namely the closeness of independent results, is obtained in the normal and correct operation of the same method on identical test material and under the same test conditions. The results show a rather good repeatability. The value of repeatability error

is 1.06% in five temperature experiments. The experimental results indicate that it is feasible for the temperature sensing using the RIA at 850nm of irradiated Ge/P co-doped fiber with 10,000 Gy after annealed sufficiently.

Summary

A novel temperature sensor based on the temperature dependent RIA of Ge/P co-doped optical fiber was proposed in the paper. The sensing principle could be explained by the the temperature dependence of color center absorption according to the configurational coordinate model. A series of experiments were carried out. When the dynamic range of the temperature sensor is -40°C to 60°C , the attenuation variation (636.57dB/km) of irradiated fiber with a total dose of 10,000 Gy in entire temperature range was greater than that of the pristine fiber (0.56dB/km). The developed temperature sensing system with 18m irradiated fiber possessed an average value sensibility of 0.1146dB/ $^{\circ}\text{C}$. The nonlinearity error was $\pm 2.75\%$, and the repeatability error was 1.06%. Compared with other fiber optic temperature sensors, the sensor proposed here showed an extremely simple structure with intensity modulation and simple manufacture. Low-cost and distributed temperature sensors can be made by changing its structure.

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